



## TIPP 2011 - Technology and Instrumentation in Particle Physics 2011

Resource utilization by the ATLAS High Level Trigger during  
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**Abstract**

In 2010 and 2011, the ATLAS experiment successfully recorded data from LHC collisions with high efficiency and excellent data quality. ATLAS employs a three-level trigger system to select events of interest for physics analyzes and detector commissioning. The trigger system consists of a custom-designed hardware trigger at level-1 and software algorithms at the two higher levels. The trigger selection is defined by a trigger menu which consists of more than 300 individual trigger signatures, such as electrons, muons, particle jets, etc. An execution of a trigger signature incurs computing and data storage costs. The composition of the deployed trigger menu depends on the instantaneous LHC luminosity, the experiment's goals for the recorded data, and the limits imposed by the available computing power, network bandwidth and storage space. This paper describes a trigger monitoring framework for assigning computing costs for individual trigger signatures and trigger menus as a whole. These costs can be extrapolated to higher luminosity allowing development of trigger menus for a higher LHC collision rate than currently achievable.

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**1. Introduction**

ATLAS is a general purpose detector [1] located at one of LHC interactions points. ATLAS has broad physics goals, but the main motivations are understanding a mechanism for electroweak symmetry breaking and searching for new physics beyond the Standard Model [2]. ATLAS employs a three-level trigger system to select events for physics analyzes, detector commissioning and calibration. A brief overview of the trigger system is given in Section 2.

In March of 2010, the LHC started colliding proton-proton beams at 7 GeV center of mass energy. Initially, each beam contained a single proton bunch with low proton density at a collision point generating fewer than one collision per beam crossing. Since then, the LHC increased the peak luminosity by more than six orders of magnitude. By August of 2011, the peak luminosity reached  $\mathcal{L} = 2.38 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  or approximately 144 million inelastic collisions per second.

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In 2010 and 2011, the ATLAS event recording rate averaged 300-400 Hz; this rate was based on available offline storage and CPU resources [3]. The initial period of increasing LHC luminosity presents unique challenges for the trigger system. Before the first collisions, extensive detector and software tests were carried out with MC simulation, test beams and cosmic muon data. Overall experimental performance was excellent, but full tests of this complex system were only possible with collision data. The trigger selections, which are applied online, are irreversible and have to be studied offline using collision data. Initially, only very simple selections using loose L1 triggers and minimum bias triggers were applied online. The collected data was then used to validate more selective HLT algorithms [4]. These algorithms were later deployed online before an increase in LHC luminosity.

It is critical that a deployed trigger menu does not exceed limits imposed by the Data Acquisition system (DAQ) and offline computing resources. To maintain constant rates, trigger selections are optimized before each significant increase in the peak LHC luminosity. An execution of a trigger signature incurs computing and data storage costs. This paper describes a trigger monitoring framework developed by the ATLAS collaboration to quantify computing costs associated with trigger signatures. This framework measures computing costs for individual trigger signatures and entire trigger menus. These costs can be extrapolated to higher luminosity using specially collected collisions data. Section 3 describes this monitoring software and presents results obtained from monitoring data collected during regular ATLAS data taking. Section 4 explains procedures for extrapolating trigger rates to higher luminosity.

## 2. Overview of the ATLAS Trigger and DAQ

The ATLAS trigger is a three level system [5, 6] which consists of a custom-designed hardware trigger at level-1 (L1) and software algorithms executing on commercially available computers at the two higher level triggers (HLT): level-2 (L2) and event filter (EF). Each level has more time than the previous level to apply a more refined selection. The corresponding design output trigger rates are 75 kHz<sup>2</sup>, 3 kHz and 200 Hz. Figure 1 outlines the Trigger and DAQ design architecture [6]. Selected events are recorded in permanent storage.

The L1 system consists of hardware based triggers and the Central Trigger Processor (CTP) that controls the L1 processing. The L1 reads data from muon, calorimeter and minimum bias detectors at the LHC collisions frequency of 40 MHz and computes trigger decisions within 2.5  $\mu$ s. The L1 muon and calorimeter triggers identify Regions Of Interest (RoI) which contain particle candidates: muons, electrons, photons, taus and particle jets. The CTP computes trigger decisions and distributes an accept signal to the sub-detectors. The detector data for accepted L1 events are stored in ReadOut Subsystem (ROS) buffers for the duration of the L2 processing.

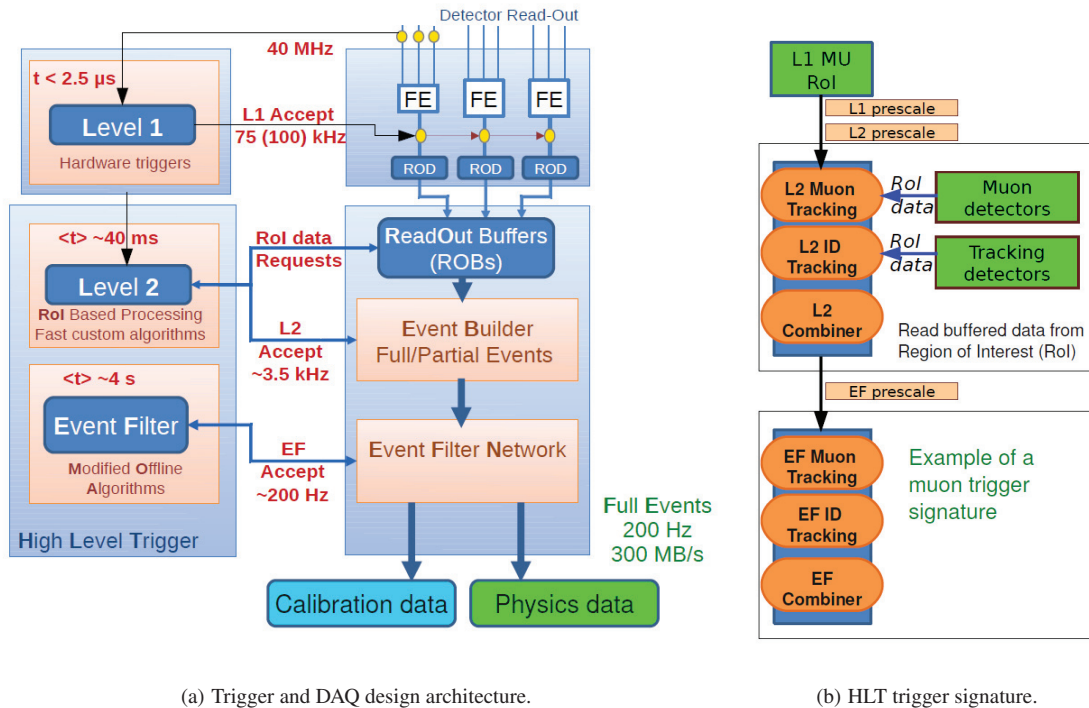
The L2 system uses fast, specialized algorithms to perform object reconstruction in a small region around L1 RoIs. The L2 algorithms read approximately 4% of detector data from the ROS buffers. Complete detector data is assembled for events accepted by the L2 and then sent to the EF farm. The EF has access to full detector data and employs offline reconstruction algorithms requiring computationally more intensive analysis. The design L2 time budget is 40 ms and the design EF budget is 4 s.

A sophisticated software framework (*steering framework*) configures and executes the HLT [7, 8]. It implements the logic of the execution of the HLT algorithms and monitors HLT performance. A processing of HLT triggers starts from an RoI position selected by the previous level. A series of HLT algorithms is executed until an event is either rejected or accepted. HLT trigger algorithms are executed sequentially, each algorithm builds on results from a previous algorithm as illustrated in Figure 1. Order of algorithm execution can influence resource utilization by the HLT triggers. For example, muon triggers first search for a track in muon detectors<sup>3</sup> and processing is terminated if no track is found. This logic results in faster event rejection avoiding unnecessary data retrieval and inner detector track reconstruction.

Scale factors can be applied to L1 or HLT signatures to reduce frequency for processing triggers: 1 means that all events are processed while 10 means that 1 in 10 events is processed. A trigger is de-activated

<sup>2</sup>The L1 system can be upgraded to 100 kHz.

<sup>3</sup>Inner tracking detectors have significantly more channels than muon tracking detectors.



(a) Trigger and DAQ design architecture.

(b) HLT trigger signature.

Fig. 1. Figures illustrate the design architecture of the DAQ and the HLT. The rates shown on the left figure are design limits. The ReadOut Buffers (ROBs) are hosted in 151 PCs of the ReadOut Subsystem (ROS PCs).

if the scale factor is negative. Scale factors can be applied at the output of L1 and inputs of L2 and EF. These scale factors are used to control trigger rates during LHC fills.

The L1 and HLT trigger rates are limited by: a) the maximum L1 rate; b) network bandwidth and CPU capacity of the ROS buffer PCs; c) a number of available CPUs. Exceeding any of these limits results in dead-time and reduces data taking efficiency. In addition, offline computing resources set a limit on the EF rate. The following section describes software which measures trigger resource utilization and predicts resource usage as a function of the LHC luminosity. This software is a primary tool for development of trigger menus to ensure that the system limits are not exceeded.

### 3. Detailed trigger monitoring framework

The HLT steering framework records monitoring data using histograms which are accessible in real time in a control room and archived for later analysis. The steering framework also captures detailed step by step information which traces an execution flow of HLT algorithms in individual events. Minimal information is recorded for every event: decisions for L1, L2 and EF triggers and unique event id. More detailed monitoring data (referred to as trigger cost data) is captured for about 1 out of 10 events, including rejected events. The detailed information includes execution times for individual algorithms and  $\eta$  and  $\phi$  coordinates of the RoIs. For the L2 algorithms, the time required to retrieve data from buffers is also recorded, together with size and location of the requested data. A typical payload size for detailed trigger cost data is about few hundred bytes.

The trigger cost data is buffered within an HLT application and the data is extracted using dedicated triggers. The buffers are attached to 1 out of 100 rejected events,<sup>4</sup> and events are recorded via the data-flow

<sup>4</sup>So that monitoring data is not recorded with events selected for physics analysis.

system as calibration events. For these events all other data is stripped to reduce bandwidth use and storage size. The cost files are processed in real time by a standard ATLAS data processing system.

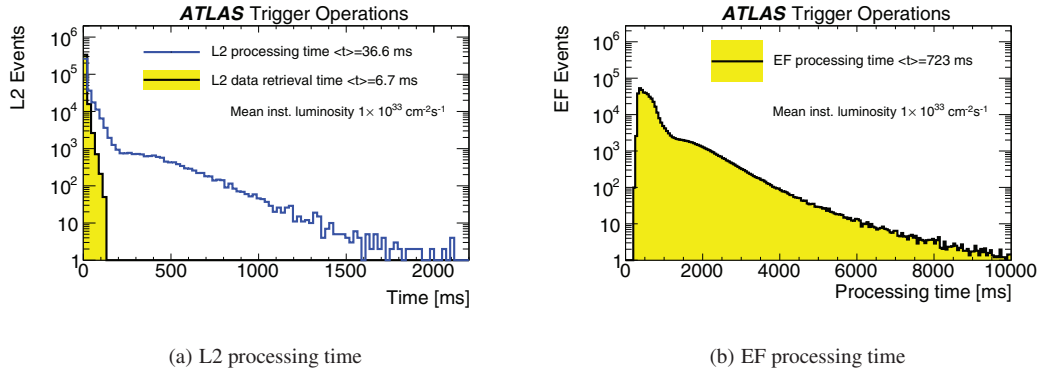


Fig. 2. Average processing times for L2 and EF events at  $\mathcal{L} = 1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ , including rejected events. The latency for data retrieval by the L2 algorithms is a small fraction of the total L2 time.

The recorded trigger cost data measures trigger rates, CPU time spent per trigger algorithm and signature, and latency for requesting data by the L2 algorithms. These measurements are automatically published using simple web pages; they are presented as sortable web tables which show top resource consumers among all of the HLT signatures and algorithms. Average event processing times are also monitored and are within limits, as shown in Figure 2. New CPUs were purchased in 2011 to cope with the further LHC luminosity increases in 2011 and 2012.

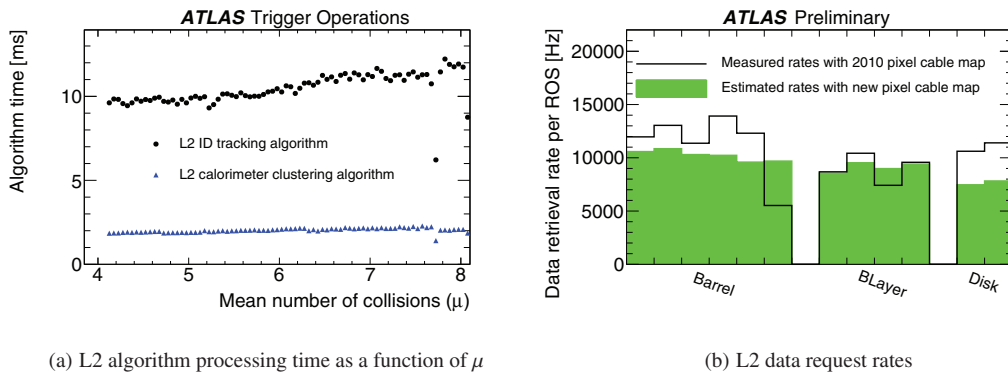


Fig. 3. Figure illustrates uses for detailed monitoring data. The left figure correlates a mean processing time with the mean number of collisions per event ( $\mu$ ). The right figure compares rates for L2 data requests for two different readout layouts for the pixel tracking detector.

The trigger cost data has additional uses beyond web monitoring. The data can be correlated with different variables, for example LHC running parameters available from ATLAS databases. This is possible because the cost data contains full record of HLT execution for individual events. One useful example is a study of CPU processing times as a function of the mean number of collisions ( $\mu$ ). Detector occupancy increases with  $\mu$  which can in turn increase processing times. Figure 3 shows the average L2 processing time for a randomly selected algorithm as function of  $\mu$ . The slow scaling behavior alleviates this concern, this is due to region based reconstruction of trigger objects.

Rate of data requests by the L2 algorithm is another of the DAQ limits. It was noticed in 2010 that there were variations in the rates of data requests between different geometrical areas of the pixel tracking

detector. This was traced to less than optimal layout of the pixel readout. The trigger cost data was used to optimize a new layout. This was possible because the data contains addresses of the individual ReadOut Buffers (ROBs), which identify corresponding ROS PC(s). Figure 3 shows that using the new readout map results in more uniform request rates; the detector was later re-cabled to use this map.

#### 4. Trigger rates

Trigger rates are monitored in real time by a control room shifter. Trigger rates can be adjusted, or triggers completely disabled, using scale factors described in Section 2. In practice, it is not possible to manually adjust hundreds of triggers in the control room. Instead, trigger menus are developed in advance for a number of pre-determined luminosity working points. The shifters can then select among the available working points to match current luminosity.

We developed an analysis framework for computing trigger rates as a function of instantaneous luminosity using collision data. This framework relies on collision data recorded using dedicated triggers (enhanced bias data). These triggers select collisions unbiased by HLT triggers and include a mixture of low and high  $p_T$  threshold L1 triggers and random triggers. About 2 million events are recorded for every stable LHC and ATLAS configuration. This number of events is sufficient to extrapolate trigger rates by a factor of ten in the LHC luminosity with better than 1 Hz precision.

Offline processing of trigger software allows emulation of the online trigger system. A complete trigger menu is evaluated on the enhanced bias data. This menu can contain new triggers or updates to existing L1 and HLT triggers. Decisions for individual triggers are recorded using the software described in Section 3. Detailed monitoring data for each event is recorded in a compact format using local files, instead of the dataflow system used online.

The recorded trigger decisions are converted to rates by normalizing event counts to the effective integrated luminosity of the enhanced bias data. The normalized event counts predict trigger rates for individual triggers and group of triggers. Figure 5 compares the predictions with actual online trigger rates for exactly the same detector conditions and LHC luminosity. The predictions are accurate to within a few percent. The differences are mostly due to variation in the mean number of pp collisions per event.

The rates are linearly extrapolated to expected LHC luminosity. Majority of high  $p_T$  triggers scale linearly with luminosity. These triggers tend to dominate bandwidth and thus overall trigger rates also scale linearly. Improving this scaling procedure is subject of ongoing work. The total rates for L1, L2 and EF are checked against the system limits described in Section 2. Triggers are enabled or disabled as necessary to ensure that the rates do not exceed these limits. If necessary, new trigger selections are developed to reduce rates. This procedure is repeated until all trigger rates satisfy the limits.

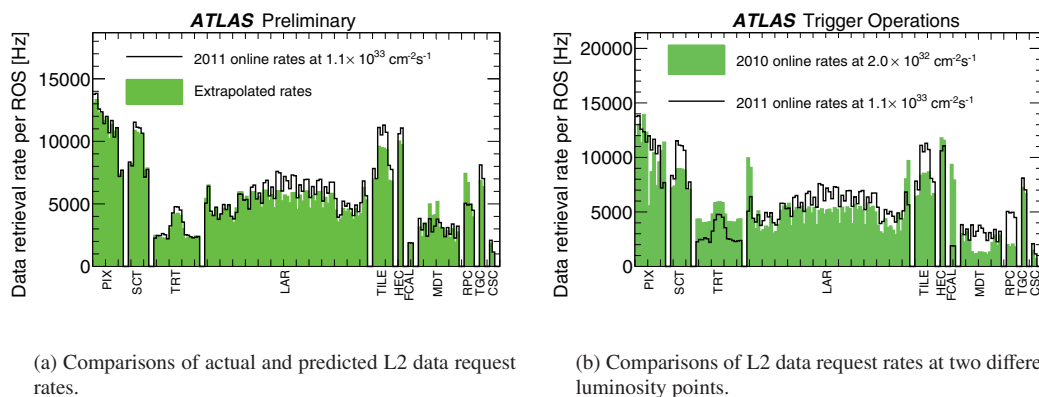


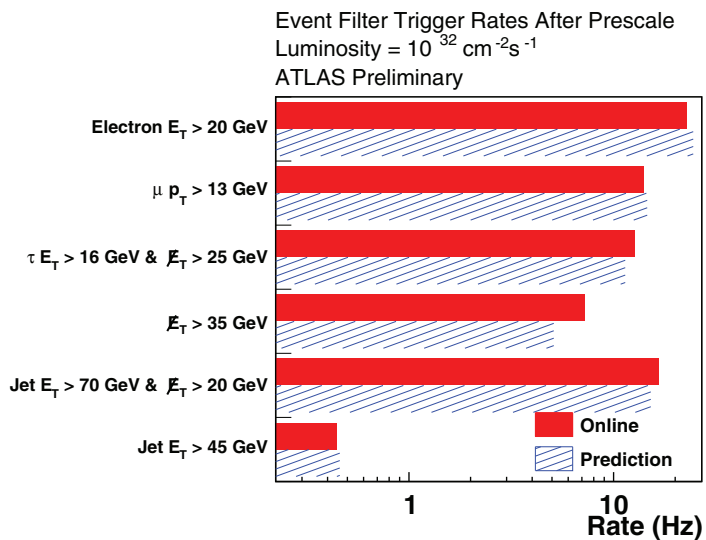
Fig. 4. Rate of data requests by L2 trigger algorithms from L2 buffer PC. Each bin on the X axis corresponds to one ROS buffer PC. The PCs are grouped by a sub-detector type.

The L2 triggers read data from RoIs with a typical size of  $\Delta R \approx 0.4$ . Retrieved data is cached by the steering framework which significantly reduces loads on the ROS PCs. Data request rates depend on many parameters: type of triggers, rate of L1 triggers, RoI size, LHC luminosity, algorithm ordering, etc. The data are requested from the ROS PCs, where each PC interfaces to read out buffers for a given sub-detector and geometrical region of the detector. Each individual ROS PC can sustain a rate of about 20 – 30 kHz depending on the sub-detector type and the size of data. If a data request rate exceeds the capacity of at least one of the ROS PCs then the system is unable to read complete detector data.

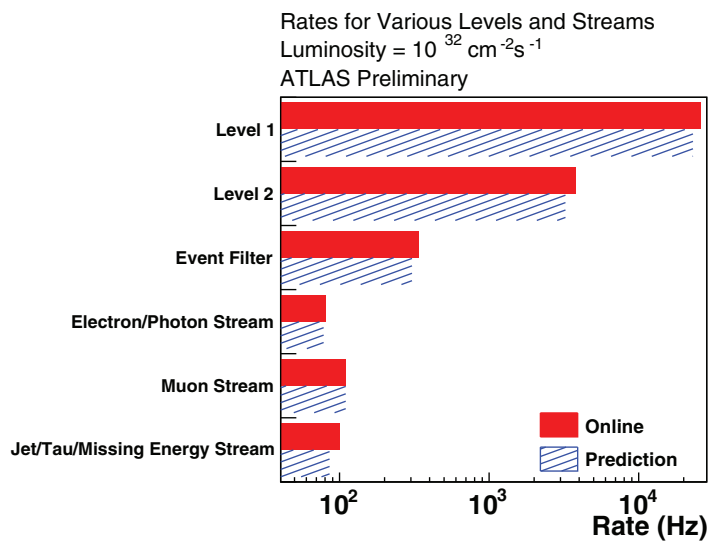
The pattern of data requests is emulated offline using the enhanced bias data. The detailed trigger cost data is extracted and used to predict the data request rates. Figure 4 shows comparisons between the predicted and actual data request rates. The predictions agree well with actual rates. This functionality is routinely used for trigger menu development to ensure that the ROS limits are not exceeded during data taking. Figure 4 also compares the ROS request rates at two luminosity points. The ROS rates do not scale proportional to luminosity because of improvements in trigger software, the optimized pixel readout and tighter trigger selections. All ROS PCs are currently being replaced with faster units. The new PCs are significantly faster than old units and are sufficient to satisfy trigger demands at expected future luminosity.

## 5. Conclusions

Rapid increases in the LHC luminosity result in large datasets which open the window on new physics. These increases also present challenges for the experiments. Trigger selections have to be constantly optimized to stay within the DAQ and offline limits while maximizing physics output. We developed software tools which allow the ATLAS experiment to quickly develop trigger menus that satisfy the system limits. These tools are easy to use and they greatly increase efficiency for optimizing trigger menus.



(a) Trigger rates for a few primary EF triggers



(b) Trigger rates for levels and streams

Fig. 5. Figures show trigger rates for individual triggers and groups of triggers. The predicted rates are compared with actual recorded rates which agree well with each other.

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